FOLDED AND UNFOLDED

USING TESSELLATION PATTERNS FOR FOLDABLE PACKAGING

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Folded and unfolded - Using tessellation patterns for foldable packaging

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ABSTRACT

This thesis is a research on origami tessellation patterns and their use in packaging design. Origami tessellations are complex polygonal patterns that can be folded into structural materials that have different properties, such as high flexibility and transformability, mechanical stiffness, and depending on the material used, they can be very lightweight. Tessellations have been studied for many different purposes but they haven't been widely used in packaging design yet.

The aim of this research is to find patterns that are suitable to be used as packaging structures to replace some of the plastic materials used in packaging, and to study the possibilities of manufacturability of said patterns. This research is a part of FinnCERES, a joint platform formed by Aalto University and VTT Technical Research Centre of Finland, that aims to create new bio-based materials and innovations for more sustainable future. The study is multidisciplinary, combining mathematics, design and material sciences. The study included a research on the correct pattern usage, experimental folding manually and via origami simulator software, creasing and folding experiments, material testing and testing manufacturing possibilities for chosen materials.

The specific brief for the research formed into creating a folded package which can protect fragile tableware, so that the package would still be visually pleasing and have a nice user-experience for the consumer when the package is opened. Through experimentation it was found that two pattern types, Miura-Ori and Waterbomb, were most suitable for the chosen purpose of the packages. The end result was a package structure which used a Waterbomb pattern with donut shaped pieces, which wraps around tableware whenever it takes a spherical form. These pieces work as cushioning inside a regular package, and protect the object from breaking.

The manufacturing possibility was still left open during the extent of this study. The manufacturability of the Miura pattern is quite certain, and it has been done elsewhere, but finding or creating the machinery would be complex, and would need to be studied further. Waterbomb pattern has a lot of challenges, but based on the tests that were conducted during this research, industrial manufacturing could be possible.

Keywords: Origami tessellations, packaging design, replacing plastics

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INTRODUCTION

BACKGROUND

My interest in packaging design was sparked during my bachelors, when I took a few courses of packaging design as minor studies. I got excited about the idea that good packaging can be a way to impact people's choices and behavior when making purchasing.

For my minor in my Master's Degree, I joined Pack-Age, an interdisciplinary packaging design project, where we were faced with real packaging challenges and worked with large companies as our clients. During Pack-Age I had an opportunity to participate in an advanced origami workshop held by Paul Jackson and had my first experiences working with tessellation patterns and folding. After that, I experimented with different types of paper and paperboard, as well as some plastic materials, to gain more understanding of the folding qualities and strengths of different materials. The interest that I had towards packaging design and branding started to grow more towards structural design and I wanted to learn how to make packaging that folds well and is functional and durable.

I also decided to pursue this subject during a Personal Project course. I wanted to explore technical aspects of folding, and learn more of how folded structures work, how different structures can be opened and closed nicely and how different structures can be folded into a smaller space and then expanded into bigger structures or to completely different shapes. I started working on tessellation patterns and folding, experimented with different materials, and learned a lot about creating structures. After I had completed the project I was convinced that packaging and packaging techniques were something I wanted to focus on in my thesis, and later on in the working life as well. Fortunately I was hired to perform my Master's thesis for a research group in FinnCERES, a collaboration with Aalto University and VTT.

OBJECTIVES AND RESEARCH QUESTIONS

This thesis is a research on the possibilities to use different geometric patterns and folded structures in packaging design. It is a study of tessellation patterns and complex origami structures that could be used in a packaging structure and be developed into solutions that would work for replacing plastic materials in packaging.

Throughout my studies, I have pursued to create design that takes issues such as durability, stackability, visual appeal and storytelling into consideration. Packaging solutions are an immensely important part of the product and delivery chain, and it is important to design and deliver packaging solutions that are functional, durable, ecological and visually interesting. This is why I decided to focus on packaging design in my Master's thesis.

This thesis will be a part of a study "Fold and Sustain" conducted for FinnCERES, a materials platform formed by Aalto University and VTT. This competence centre aims to develop new materials for a more sustainable future.

The project is multidisciplinary, combining mathematics, design and materials sciences. I am working as a research assistant for Kirsi Peltonen, Senior Lecturer for the Department of Mathematics and Systems Analysis, and in co-operation with Jarmo Kouko, Senior Scientist at VTT Technical Research Centre of Finland. The project is shared with Oleg Galkin, from Visual Communication Design, who is also making his thesis for this project.

My role as a Master's thesis worker in this project is to innovate new folded packaging solutions, that are suitable for industrial production, using paper/paperboard. The aim is to find solutions to replace plastic packaging.

My primary research questions are:

1. How to implement tessellation patterns into packaging design?
2. What kind of benefits can such a structure bring to a package design?

Underlying questions which guide my research process are as follows:

• How to implement complex origami structures into packaging something fragile?

• How to find ways to replace plastic materials in packaging design and reduce packaging materials to create less waste materials?

RESEARCH GOALS

The main goals of this research were to study the opportunities of tessellation patterns and foldability for possible packaging solutions to replace plastics. The instruction was to create alternative materials for plastics used in packaging, but it was not defined what would be packaged or what the functions of the package should be. This was a bit different approach to packaging design than usual, since we started from a very material-centric point of view and not from a specific brief on how to pack a certain object or product.

One of the goals of this research was to find out if it would be possible to manufacture these patterns by using a rolling nip device or some other kind of machinery. This would prove that the patterns could be industrially manufactured in the packaging industry in the future .

This thesis is divided into four parts:

1. A description of the project goals and discussion of the chosen methodology, practice-based research, followed by a description of the methods used to achieve the project goals.

2. A literature overview on origami, tessellation patterns and folded structures, and the mathematical practices behind the patterns.

3. An overview on packaging design, sustainable packaging materials, and folded packaging.

4. An analysis of the process of creating the patterns and applications for folded packaging, discussion, and conclusion regarding the findings.

FINNCERES

FinnCERES is a materials cluster formed by Aalto University and VTT, Technical Research Centre of Finland. CERES aims is to develop new bio-based materials, and support Finnish bio-economic research, with the following goals:

- The use of new biomaterials to replace or capture plastics
- Overpass the textile fibre gap
- Development of light-weight materials for various end-uses
- Evaluation of solutions for partly bio-based electronics and many more

(FinnCERES, Research)

FinnCERES is focused on finding ways to use bio-based materials to answer to perhaps the most urgent questions of our times, those of climate change and the insufficiency of resources. FinnCERES studies lignocellulose and the disassembly and reassembly of lignocellulose. The aim is to create new ecological products with smarter resources.

FinnCERES seeks to explore lignocellulose as a sustainable alternative to plastic. With the production of bio-based and biodegradable materials, they seek to reduce the utilization of plastic. Yet a large amount of structural and material research is needed, as the alternative solution needs to be both fit in its mechanical and functional properties, as well as low-cost. (FinnCERES, Research)

The Fold and Sustain project was set up to tackle these challenges by studying origami tessellation patterns and creating folded structures using cellulose based board materials as a better solution for replacement of plastic materials.

METHODOLOGY AND METHODS

Research has conventionally regarded to underpin in ”knowledge”, which in itself has been viewed as generalisable as well as transferable (Smith & Dean, 2009, 2). This means that knowledge should also be withheld true when put into another concept or event, and that knowledge should be understood by others in a way that is the same or similar to that than the original intention. However, Smith and Dean note that creative arts has had its struggles under these conventional descriptions of research and knowledge, as knowledge is often perceived as verbal or numerical, where knowledge under arts can be, for example, sonic or visual. Furthermore, knowledge in art can be ”unstable, ambiguous and multidimensional” or ”emotionally or affectively changed” (ibid).

When we look at research through the lens of creative arts or design, we must question the prevalent notion that ”knowledge” means unchanging numerical data, precise and non-changing written proof, or absolute, subjective truths. And as the concept of knowledge is called into question, so must the understanding of what ”research” means also be challenged. To undertake a design research with an acceptance of these notions, this thesis utilizes a combination of practice-based and practice-led research.

PRACTICE-BASED AND PRACTICE-LED RESEARCH

Practice-led research is one of the largest developments in academics in the past few decades. It brings new perspectives to thinking and conducting research and brings awareness to different kinds of knowledge that can rise from creative processes and creative practices. Smith and Dean (2009, 8) describe the two-way influence of practice-led research: just as creative practise brings about innovations and weight to academic research, so does academic research also have a positive impact on creative practices.

As Linda Candy (2006, 2) puts it, practice-related research can be divided into two types of research: practice-based and practice-led. A practice-based research is an investigation conducted to, in part, gain new knowledge of a practice and the outcomes of that practice. The core result of a practice-based research is a contribution to knowledge, which takes the form of a creative artefact, such as images, exhibition, design or digital media. A practice-led research studies the nature of that practice and seeks to input operational significance for that practice. The core result of a practice-led research is new understanding about that practice.

Laurene Vaughan (2017, 12) notes that with practice-based research, the location of the action (the research) is the location of the practice. Vaughan argues that the research contribution of a professional designer slightly differs both from a traditional researcher as well as a traditional designer, as the contribution of a practice-based design research is both “material and intellectual”, and extends to the worlds of commerce, culture, and well-being.

COLLABORATION AND PROCESS FLOW

Practice-based research is often collaborative in its nature, as it seeks to utilize knowledge and practises from different views and different viewpoints, such as academic theories combined with creative outputs. This research was collaborative as well, and the team consisted of people from different areas of specialisation.

We received the brief for the research from Kirsi Peltonen who works in the Department of Mathematics and System Analysis, and Jarmo Kouko, from VTT. Together with my research partner, we took on different aspects of the research. During the research we held regular meetings with Peltonen, to present our progress and to receive knowledge of the mathematical possibilities and limitations for the research. We also held Skype conferences with Kouko to learn about the practical opportunities presented by their research lab in terms of the possible production of the patterns. The process was iterative and required an extensive amount of collaboration, which ensured we were able to maintain a scientific approach to the process and ensure the requirements of practical producibility would be as realistic as possible.

EMPIRICAL STUDIES

The research process relied heavily on an iterative optimization process. Each prototype of a pattern was given a hypothesis on its behavior and its functionalities and was studied after its completion. I experimented with different thickness of materials and different types of folding. In the first stages of the research, the prototypes were observed using a 3D origami software, but as I gained more knowledge as well as developed my visual eye and material understanding, I could proceed to tangible prototyping faster.

In addition to material experimentations, an important aspect of the empirical research was to test the prototypes for different functions and different objects. As the research went on I decided to focus on creating durable packaging for fragile objects, as they seemed a type of products that would benefit the most from a tessellated structure in their packaging.

The third part of the empirical research dealt with the more creative and more subjective parts of the research. The research did not only set out to find a tessellation pattern that simply works, in a research center or a proven theory. Rather, the packaging was created to be liked, to provoke interest and positive feelings, a sense that the packaging would not only replace a plastic option but to be an option so much better that customers would opt-in to use it even if given a choice.

TESSELLATION PATTERNS & COMPLEX ORIGAMI

It is in the nature of organic things to take a form that is somehow folded. From our DNA to the ground under us, folds are everywhere. Different materials come with different folded structures, and organisms in nature, such as leaves on trees, often follow a regular pattern with a folded structure. Folding can be as simple as making just a pleat on paper, or it can go into very complex structures.

This chapter presents the definitions of origami and tessellation patterns and the usual terminology around folding these patterns. This chapter will also present some properties that these folding patterns can have, and applications these patterns have been used for. The last section will be an overview of the manufacturing methods which have been developed for creating these patterns industrially.

ORIGINS

Origami originates from Japan, and folded paper has been ”an art form” for around 15 centuries (Lang, 2003, 3). The word “oru” means a fold and “kami” means paper, so at its simplest origami is folding of paper. Although it is often related to folding animal shapes and being art and craft, folding patterns that are based on the same geometries can be used widely to different purposes, and be transferred to different materials besides paper. Lang states that even though the representational or figurative origami is the one that people usually recognize when talking about origamic designs, there is also a long history for non-representational folding that has developed into the complex mathematical origami tessellations that we see today (Lang, 2018, XV-XVI).

Originally the word tessellation comes from the Latin word “tessella” which means a small square, having its roots in geometric designs of Islamic mosaic patterns. In the hands of origami artists, these patterns have turned into complex pleats and twists - origami tessellations. (Gjerde, 2009, 2.) As defined by Benjamin DiLeonardo-Parker: “Tessellations are patterns of polygons that tile regularly on a plane. Origami tessellations accomplish this using one sheet of paper without cuts, generally using pleats and twists, or mountainous corrugations”. Instead of resembling an animal or an object, as in traditional origami, origami tessellations are repeating a geometric pattern that creates a structure. (DiLeonardo-Parker, 2016, VII, 2)

As a tool for creating forms, origami and understanding some mathematical principles of folding are great assets for a designer. Paul Jackson argues that since folding and origami is often related to folding animals and often perceived as merely crafts, it hasn’t reached much popularity among designers. However, all designers fold, and folding techniques and foldable patterns can be used from fashion to architecture, and it has been gaining more and more interest in the design field. (Jackson, 2011, 9.)

LEADING NAMES IN THE FIELD

Stemberg (2010, 359) discusses the legacy of Josef Albers, the Bauhaus artist, whose teachings on origami tessellations had an effect on the studies of tessellation patterns and through this, an effect on architecture and design. During the 1920s and 1930s, Albers hosted design workshops, where he gave his students instructions to form 3D objects only by folding paper. Some photographic evidence from the era suggests that even at this time, a knowledge of collapsible patterns was passed forward.

During the 1970s, Ron Resch, who is a computer scientist and an artist, started to use mathematical and computational algorithms to design and fold paper forms (Lang, 2018, xvii). Another computer scientist named David Huffman drew from Resch’s work and developed new concepts, and from the works of these two computer scientists grew a new line of research into geometric folding. This thread of research combined mathematics and art equally: “algorithms, existence, and complexity paired with statement, expression, and aesthetic” (ibid.). A part of Resch’s studies was the study on different variations of non-flat-foldable triangular and square-based Waterbomb patterns.

Image 1. *Josef Albers teaching folding thecniques, 1946.*

Image 2. *Folded paper sculpture from ”Made with Paper Show” by Ron Resch, 1967.*

One of the leading origami masters in the world is Robert Lang. He uses the principles of mathematics and engineering to create intricate designs. In his biography, he is described as ”one of the pioneers of the cross-disciplinary marriage of origami with mathematics”. Besides having hosted his art in museums such as MoMa in New York and the Nippon Museum Of Origami in Japan, he has been an engineering consultant to products such as airbags and space telescopes. (About Robert J. Lang, Bibliography.)

One origami and paper artist, who had a big effect on my interest in the subject, is Paul Jackson, who teaches folding workshops around the world and has written good instructionals about folding and created a box-folding system, that is very useful for designers.

Other leading names in the field include for example Jun Mitani, an Information and Systems professor under the Faculty of Engineering in the University of Tsukuba, who has focused on curved folds and Eric Gjerde, a Minneapolis-London-based, self-proclaimed ”paperlogist”, paper artist and teacher, and Ekaterina Lukasheva, artist and author focused on modular origami technique, kusudamas, and papercraft geometric objects.

MATHEMATICS AND TERMINOLOGY

Eric Gjerde (2009, 3) notes that most origami tessellations take on one of six different tessellation geometries. These six geometries are divided into two: regular tessellations and semiregular tessellations. Regular tessellations are formed by single, repeating shapes: equilateral triangles, squares, and hexagons, presented in the first row in the figure below. A semiregular tessellation means that shapes are arranged around a single point, but the types of shapes are different. Three very common examples of semiregular origami tessellations are presented in the *Figure 1.* under regular tessellations. (Gjerde, 2009, 3)

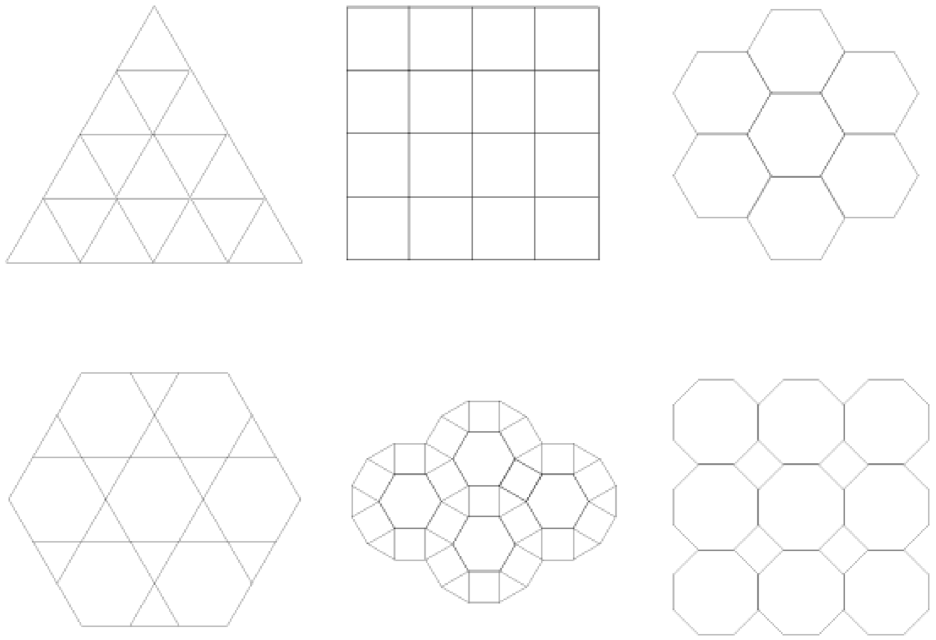


Figure 1. *Regular and semiregular tessellation geometries (Gjerde, 2009, 3).*

In its simplest form, an origami consists of flat surfaces, straight lines which are called creases, and the meeting points of these creases, called vertices. The areas surrounding these creases are called facets. The creation of an origami usually starts with some kind of a grid - the crease pattern (Lang, 2018, 5.). The crease pattern is the blueprint of the folding and indicates to which direction each line should be folded. The directions of folds are called the mountain fold and the valley fold.

The mountain fold means a fold which is folded away from you, whereas in valley fold, the fold is folded towards you. Mountain and valley folds are usually marked on the pattern with different colors, or using an even line to mark the other and a dashed line to the other, yet there is no standard way to mark them. (Lang, 2018, 7-9.)

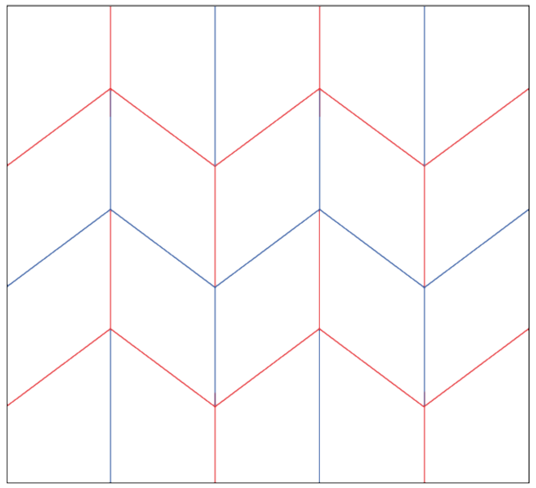
When discussing origami tessellations, one of the most important terms is flat-foldability, meaning if the form can be folded flat or not. Lang states that in flat-foldable origamis, all facets are flat and coplanar, creases have a fold angle of either 0 or 180 degrees, and the paper has zero thickness (Lang, 2018, 4).

The “flat-foldable” origami model is then built on simplifying assumptions. Firstly, zero-thickness paper doesn’t exist, and secondly, an unfolded crease pattern cannot transform itself into folded and back as described. While the model does not, then, provide achievable results (i.e a functioning folding sequence), it helps to understand the basic background of folding, and it still has value in providing algorithms and practical guides which can help in the creation of useful and practical folded shapes (Lang, 2018, 5).

MIURA-ORI

One of the most known patterns is Miura-ori, made famous by Japanese astrophysicist Koryo Miura. Even though the pattern is named by him, it has existed long before. Stemberg (2010, 352) refers to a 14th century painting which has a clear Miura pattern folded on a piece of clothing, and Lang (2018, 112) presents a figure instructing how to fold Miura pattern, dated back to the 15th century, from Li Tre Trattati, even though at the time the folding pattern had not been named. Miura-ori exists in many organisms in nature as well, but this specific collapsible pattern has been under extensive research because of its unique properties.

Miura-ori is essentially a pattern which alternates mountain and valley “zigzags”. Moreover, the crease pattern consists of parallelograms in rows and columns, so that the creases form zigzag lines one way, and collinear lines the other way (Lang, 2018, 109.) As the mountain and valley folds alternate, the pattern opens and closes without natural curvature, maintaining it’s flat composition. Lang notes that one of the unique aspects of Miura-ori is its ability to ”fold rigidly with a single degree of freedom” (Lang, 2018, 109). This means that one can fold and unfold the entire pattern with a single motion as long as it has rigid facets throughout the pattern. Stemberg (2010, 350) states Miura-ori is a rigid collapsible origami pattern, which can open and close by one continuous motion when pulled or pushed from opposite corners.



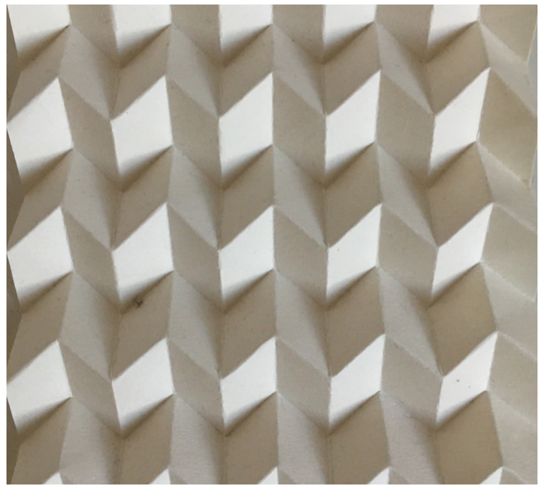


Image 3. & 4. *Miura as a crease pattern, and as a folded structure.*

Semigeneralized Miura-oris create patterns that are strictly periodic in one direction at all folded states, as well as have a single degree of freedom in their folding motion (Lang, 2018, 164). Additional flexibility is added by eliminating edges in the pattern and partly uniting corners of the tessellation. When these edges are completely eliminated and the two types of folds are completely united, a new type of motion is enabled in the pattern. The motion is no longer curved along the minor-fold direction and linear along the perpendicular direction, but straight along the minor-fold direction, and curved along the perpendicular direction. The pattern can now move in both ways and in mixtures of the two. (Lang, 2018, 169.) This new pattern is called the Waterbomb tessellation, which has two periodic motions which can be seen as the tessellation is flexed: a linear motion and a cylindrical motion (ibid. 171).

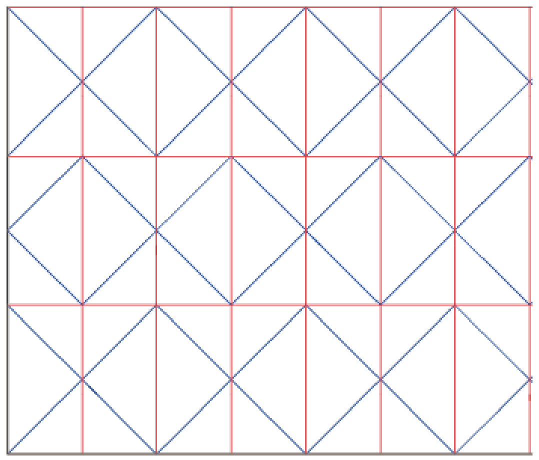


Image 5. & 6. *Waterbomb as a crease pattern, and as a folded structure.*

MAIN THEOREMS

There are two main theorems which make up the fundamentals for mathematical approaches to origami: Maekawa's theorem and Kawasaki's theorem. Maekawa's theorem applies in origami model crease patterns whenever the paper folds flat. The theorem states that when looking at any vertex (a point where angles, curves or lines meet, such as an angle where two lines meet) in the interior of the paper in a flat origami crease pattern, the difference between mountain creases and valley creases is always two (Fei & Sujan, 2013, 1132).

Kawasaki's theorem, named after one of its discoverers Toshikazu Kawasaki, contributes to the mathematics of paper folding. The theorem describes the crease patterns with a single vertex, which form a flat figure when folded (Fei & Sujan, 2013, 1132). According to the theorem, a crease pattern is foldable "only if all the sequences of angles surrounding each (interior) vertex can be summed to 180 degrees" (ibid.).

When you take any crease pattern and apply the Kawasaki's theorem to it, you are able to determine if the crease pattern is locally flat-foldable. In a locally flat-foldable pattern the crease near the vertex can be flat-folded. (Alsina et al. 2010, 53.)

PRACTICAL IMPLEMENTATIONS OF THE PATTERNS

Architects have always been inspired by the possibilities that origami can offer for designing the most interesting structures. There are great examples of buildings around the world that utilise origami tessellation patterns in their design and when an origami patterns is implemented to the size of a building, the results can be truly amazing. Different foldable structures also make it possible to achieve movable and transforming structures that can function well for for example in shelters and other movable housing.

In the field of design, tessellation patterns have also been seen in fashion design to create pleated shapes and volume to the fabric. There is a long history of utilizing tessellation patterns in fashion and textile design. Jean-Charles Trebbi describes an intricate, long-held tradition of a French atelier to create pleated textiles by using two sided mold in which the pattern has been folded, and which is then steamed to fix the pattern on the fabric in between the molds (2012, 68). Other well-known examples include Le Klint lamp shade range (ibid, 44) which is still manufactured by folding manually and sold around the world.

There are beautiful examples in design and architecture that use folded structures and tessellation, but the use of these patterns reaches far beyond that and offer interesting opportunities for technical applications as well. In 1995, a satellite called Space Flyer Unit was launched to space. It was created by using the Miura-ori pattern, and it allowed the structure of the satellite to be in a smaller form when launched to space and then expand to its full size. (Garcia, 2017)

From top left:
Image 7.
Helios House, an origami inspired gas station in Los Angeles.

Image 8.
Origami Pavilion designed by Tal Friedman.

Image 9.
Tote bag designed by Issey Miyake for Iittala.

Top right:
Image 10.
Le Klint lamp shade model 153 by Andreas Hansen.

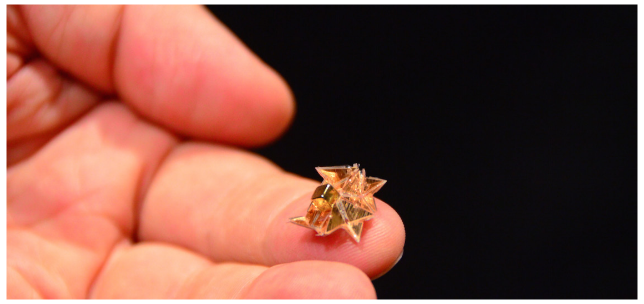
Image 11a & b.
Origami inspired fashion Raised / Unfolded, by Jule Wailbel.

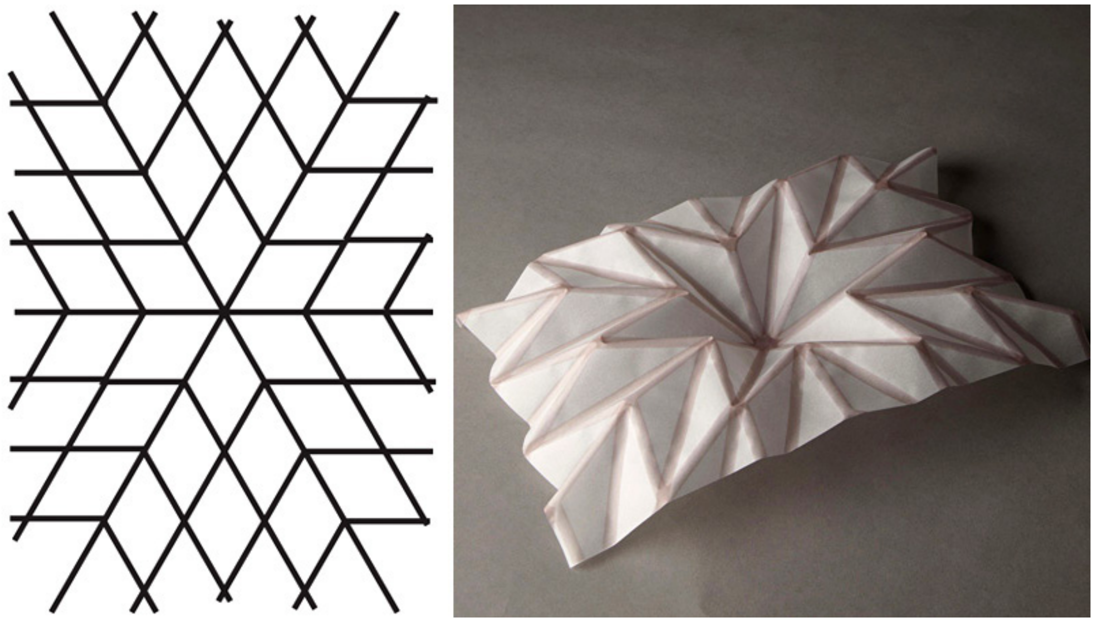





The space program NASA utilized origami folds to build effective spacecraft components. Panels used in space missions already use simple folds, but there is an increasing interest to study the incorporation of more intricate patterns, which would make the deployment and mechanical structures of the objects simpler. According to researchers, origami could be used to utilize space solar power, and sending solar arrays to space could be easier utilizing origami, as they could be folded and packed into a single rocket launch. The implementation of a Miura fold for solar array ensures a simplified mechanical structure, as it only needs one input to deploy it - with a Miura fold, it opens and closes only by pulling it from one corner (Greicius, 2014).

Tessellations have also been used in medicine. Expandable heart stents, stretching from 12mm to 23mm in diameter, were designed at the University of Oxford by Dr. Zhong You and Kaori Kuribayashi, for prevention of collapsing arteries (Trebbi, 17, 2012).





On top row:
***Image 12.** Origami heart stent by Zhong You and Kaori Kuribayashi.*
***Image 13.** Self-folding Origami Robot, MIT.*

Under:
***Image 14 a & b.** Waterbased Inkjet prints self-folding tessellations.*

Several interesting experiments have been done, also with more commercial and experimental approaches, such as a waterbased inkjet print for self folding origami, 3D printed pasta that folds when dropped into the boiling water, and a self folding origami robot that can perform different functions such as walk and swim.

I was able to study the practical implementations of tessellation patterns during my visit to Stuttgart University, at the Institute of Aircraft Design, where technical tessellations are studied and being tested for Aircraft core structures. I observed the molding and heating techniques used to set the patterns in place and make the structure rigid and lasting. Not only was this visit an excellent opportunity to learn about the different methods used for folding structures to make them rigid, but it also enabled me to personally view the strong yet lightweight abilities of the patterns. This helped me formulate the research-based hypothesis for my research questions and research objectives.

MANUFACTURING THE PATTERNS

Origami structures have interested scholars in recent years due to their good mechanical properties and their highly lightweight qualities. In engineering applications, they have been used for example in the architectural field and the automotive domain (Wang et al., 2018, 827). Fabrication has received less focus than structural design and foldability analysis, and efficient and high-quality fabrication of an origami structure is difficult because of large fluctuations and their intricate shapes. While mass-production and efficient fabrication are important considering the practical applications of origami structures, manufacturing technologies for the production of origami structures has not been largely studied.

Elsayed and Basily present a way to use continuous manufacturing techniques for a new sheet material folding technology (Elsayed & Basily, 1, 2004). Elsayed and Basily designed and created a machine which can produce sheet folded patterns continuously. The machine utilises a technique in which sheet material is pre-folded ”through a set of sequential and circumferentially grooved rollers” (ibid, 10), after which there’s a set of cross folding rollers which have specific patterns engraved in them.

Elsayed and Basily note (2004, 1) that folding technology is one of the most efficient processes when it comes to shaping and structurally forming sheet materials. They note that other production methods, such as forging or pressing, can produce similar-looking three-dimensional patterns, but they can be costly, and the mechanical properties of the end-result patterns may differ significantly (ibid, 1.)

This is exceptionally harmful when the sheet material is thin, as in those occasions any variation in sheet thickness or mechanical properties is problematic. They also note, that their continuous sheet folding technique can produce intricate structures quickly and economically. (Basily & Elsayed, 2004, 2)

Koryo Miura was the first to study the properties of a partly cylindrical tube structure, while Elsayed and Basily used sets of rollers with origami structure to create folded sheet (Elsayed and Basily, 2004, 2). Khaliulin and Dvoyeglazov used deformable mold, connected through hingnes by metal pieces, to produce folded structure, and Schenk et al. utilized a vacuum pressure assisted method to fabricate metal folded sheet (ibid.). Paik et al. used a shape memory alloy actuator, while Wang et al. used a vacuum forming process to fabricate place and curve surface polymeric origami. Wang et al note that none of the research so far has been efficient to fabricate origami tube efficiently, and has only been focused on enabling the fabrication of simply folded structures. (Wang et al., 2018, 827.)

PACKAGING DESIGN & FOLDABLE PACKAGING

One of the main functions of a package is to protect the product inside it, whether it is sitting at a storage space as a part of a logistics chain, waiting to be stacked and delivered, or at a store to be seen and purchased by a customer. Another main function of a package is to give the consumer information about the product inside, such as a product description, instructions on handling the product, product origins or a best-before date.

DuPuis and Silva state the six purposes of packaging as following:

- Containment
- Security
- Protection
- Convenience
- Information
- Marketing

(DuPuis & Silva, 2008, 106)

From a commercial point-of-view, the most important factors of packaging are noticeability and recognizability of the product at a store shelf, and that all the necessary information can quickly be found on the packaging. The package should also be intact from the delivery, and be user-friendly: easy to open and use, and simple and easy enough to recycle. (Järvi-Kääriäinen, Leppänen-Turkula, 2002, 17-19.)

Packaging can make a big difference in the purchasing habits, recycling and reusing of the materials. Overpacking and covering objects with layers of plastic is unnecessary, and in addition to creating tons of waste, it also affects the opening experience negatively. Innovating better material solutions into packaging through innovative designs is crucial for the sake of the environment. There is a constant need for new material innovations, and packaging does not need to be an afterthought that is stamped upon a ready-made, more ecological product.

As Ellicott & Roncarelli (2010, 34) note, innovations in the packaging field often arise alongside social trends as responses to it. Ellicott and Roncarelli argue that our causes for material innovation are currently brought up with the issues we are currently facing, including an increase in life expectancy and the growing popularity of local production and manufacturing of food. Ellicott and Roncarelli note (2010, 34) that “by using a material in an unfamiliar context and by expanding its unrealized potential, the designer can make a significant impact at the shelf level”.

According to Ellicott and Roncarelli (2010, 120), surveys state more than two-thirds of the population would prefer recycled packaging materials and would agree to pay more if a package was environmentally responsible. Ellicott and Roncarelli note that sustainable packaging and the ways to develop it are an area of special interest to “standards, organizations, government, agencies, consumers, designers, packagers, and retailers” (2010, 120).

ENVIRONMENTALLY FRIENDLY PACKAGING

Miller and Aldridge (2012, 39) note that designing for the retail environment and designing in a way that encourages environmentally friendly behaviour should not present a conflict. Designing for both of these purposes starts with understanding how materials function and how they can be disposed of. For this, they suggest taking the ”reuse, reduce, recycle” -mentality as the core for environmental yet consumer-oriented packaging design.

One practical method for reducing packaging include lightweighting materials, which means to reduce their wall thickness to save weight. Reducing the overall size of packaging and avoiding unnecessary packaging materials are also good examples of reducing packaging materials (Miller & Aldridge, 2012, 41). Even though tessellated structures use more material than a simple packaging structure, they enable the material itself to be thinner and lighter because the structure makes the material more durable.

The practice of reusing materials as a form of environmental friendliness is a little bit more complex. Miller and Aldridge note (2012, 45) that in order to get reuse to work, “it must make the purchase of another product unnecessary”. This means that it is naturally better to reuse a plastic bottle by filling it with water than to by a new bottle of water, but buying an unnecessary consumer good one wouldn’t normally buy (such as a bird feeder made out of plastic bottles), does nothing good for the environment.

Scandinavian and Northern European countries lead the way when it comes to recycling, and it is sometimes difficult to comprehend how early stages some countries are in when it comes to recycling. It is easy to imagine that recycling would always be more energy-efficient than manufacturing a new product, yet the recycling process isn’t always that straight-forward. The easiness of sorting and the efficiency of collection and reprocessing must all be taken into consideration. For a product to be recycled, it must be built so that its recycling is user-friendly: simple, intuitive and fast. When considering the reprocessing process of a recycled material, we have to weigh in the logistics, sorting and cleaning processes and the carbon footprint these bring.

Given these limitations and difficulties that environmental packaging brings, some conclusions have been drawn for this research paper. It was necessary that the implementation of the packaging I found would replace a less environmentally friendly solution, not be an additional product next to less environmentally friendly solutions. This is an important distinction, drawn from the discussion on the problems of reusing materials. This means that the packaging product needs to be, from the consumer’s point of view, not only as good, but better, than the other solutions. From a retailer’s point of view it is also important it would not be more expensive, as in that case they would not buy it, which means it would never have any real environmental impact.

HOW TO REPLACE PLASTICS?

According to FinnCERES, the annual production mass of plastic every year is nearly 280 million tonnes, and most of this plastic ends up in the environment, with severe negative impact to marine life and other ecosystems. (https://finnceres.fi/research/, retrieved 1.8.2019)

According to the European Parliament (Plastic in the ocean: the facts, effects and new EU rules, 2018), in 2018, more than 150 tonnes of plastic existed in the oceans, and between 4.8 to 12.7 tonnes of plastic enter the oceans every year. 49 percent of marine litter consists of single-use plastics (SUP). According to a research paper by the World Economic Forum on the future of plastics economy, by 2050, the ocean could contain more plastic than fish, when calculated by weight (World Economic Forum, 2016, 7).

In a state of the world where everything is slowly being covered by plastic and global warming is in an alarming state, finding new kind of solutions to replace plastics is essential. Wood is a great opportunity in a country like Finland where forests are covering a great deal of the landscape. Cellulose as an industry has renewed itself from paper manufacturing to great new innovations. VTT is developing and testing cellulose-based materials – wood fibre can be turned into strings which can be used for example in the textile industry or into cups that resemble plastic cups. It can also be turned into bathroom tilings, thin sheets that look like transparent plastic, or into many other forms. (Koskenlaakso, 2017)

FOLDABLE / FLEXIBLE PACKAGING

Starting from a milk carton, all board based packaging can be folded, but the focus of this research is on those folded and flexible structural designs in packaging design which bring something new and innovative to the field.

Flexible packaging is essentially any package that isn't completely rigid: when talking about flexible packaging, it usually refers to packaging materials that are soft and transformable and can adapt to different shapes. These are often pouches, foil, plastic films and other "soft" materials, not necessarily flexible in a sense that folded structures are. (Shijan et al., 2017, 5.) The type of flexible packaging I am interested in is the type of packages that are only flexible under the designed structure, created by folding and more specifically by using the tessellation patterns. I will refer to these packages as "tessellation packages".

Packaging which utilizes origami-based structures isn't that common in the industry, and there is a reason for that - making a complicated structure is usually difficult to manufacture and it uses more material resources, so it needs to be well reasoned. Simple cardboard box can often be a good solution instead. Most of the packaging I found during this project were from a luxury section of packaging, such as champagne and perfume packages, or design concepts that haven't been released into real production. Presumably this is because of the challenging manufacturability of the patterns.

The designs that utilize folded origami tessellation patterns are usually utilising the collapsable abilities of these patterns. When starting this research, I started by benchmarking folded packaging solutions to have an idea of what has been done before in the field of packaging. I divided tessellation packages into four different types. Firstly, some packages have tessellation patterns that open from a collapsed form to ease the logistics chain and remove space during the transportation of the packages.

One good example of folded packaging that has a function in using a folded structure is Expanding bowl designed by Tomorrow Machine (Images 15. & 16.). It is folded to a compact size to save space when transported, and in use, the bowl has freezer dried food inside which will expand when hot water is added. The deployable qualities of folded structures can be utilized in packaging something to save space. Another example of this is be Mathias van de Walle' origami inspired champagne packaging "Clicq'Up" for Veuve Clicquot, which is a foldable package and can be opened from a collapsed flat form into an ice bucket for the champagne (Images 17. & 18.).

Images 15. and 16.

Expanding Bowl, by Tomorrow Machine

Secondly, some packages have tessellation patterns to make the recycling of the product as easy as possible, so the package will fold flat and nice with a little press. This is shown for example in the collapsable folded structured packaging in Petar Pavlov's concept for Doritos chips packaging (Image 19.). It utilises the triangular shape of Doritos and it will fold flat when empty. It also opens nicely because of the triangular tessellation pattern. As another example I present Pair Champagne packaging (Images 20. & 21.) by Natasha Frolova & Louise Olofsson, which holds two bottles of sparkling wine, and after using the package, it can be pushed flat into a smaller size and reused or recycled.

Thirdly, many tessellation packages have the pattern merely for decoration, and the pattern itself doesn't serve much function. The tesselation pattern creates an interesting shape and surface structure to the packaging and makes it more appealing. Wine packaging done for Quartz Champagne (Image 23.), designed by Max Molitor and Cajza Nyden would be one example of this.

Fourthly, some designs utilise the tessellation pattern as a way to use the product until the end, or as well as possible. Often, the folded structure was created to make it easier to squeeze something out of the package or expand the package when in use. This is presented in Aube's wine bag-in-a-box (Image 24. & 25.), designed by Veronica Kjellberg and Mila Rodriguez, which utilises the collapsable abilities of the folding pattern so that all the wine can be squeezed out, and once empty, the product can be pushed flat and easily recycled. A concept for Colgate toothpaste (Image 22.) by Nicole Panuzzo relies in this squeezing motion as well. The design uses an accordion-like structure that makes it possible to squeeze the tube empty easily.

Left:
Image 17 & 18.
Clicq'Up Champagne packaging turns into an ice bucket.

Image 19.
Doritos packaging concept.

Up:
Images 20 & 21.
Pair Champagne folds flat

Image 22.
Colgate Concept for easily squeezable packaging.

Image 23.
Folded packaging of Quartz Champagne.

Images 24. & 25.
Aube Bag-in-a-Box Wine can be pressed flat when empty.

THE PROCESS

While I went through the literature for tessellation patterns and folding and benchmarked packaging that uses these structures, I also started folding things myself from the beginning. During my process I investigated patterns to create them and fold them, analysed the results, and then repeated the process again. As I folded different kind of pattern types I grew my knowledge on the properties of different pattern types, and on how certain geometries work when folded. In this section, I present my phases and self-reflections step by step.

Step 1: Searching for patterns to use

At the first phase of the project, I went through existing patterns and searched for master origami artists and professionals that fold. Based on the patterns I found, and learning about folding techniques, I started to recreate these patterns myself. It was very educational to see the patterns on a flat form as lines going around the pattern, and try to envision how it will fold and what it will look like when created in 3D form.

Step 2: Creating vector files

The process of making tessellations and testing them starts by creating the pattern. I created the patterns as vector files in Illustrator. With this process, the pattern was easily adjustable and scalable, and the pattern was possible to cut with a laser cutter and later, with a vinyl cutter. At first, tracing the patterns line by line took some time, but after using it for a while, a small library of patterns was formed, and I was able to adjust these patterns to make new ones and scale them to different sizes.

Step 3: Origami Simulator

To figure out how the patterns would function when folded without creasing and folding it first, 3D programming or coding skills would have been very useful for the process to easily demonstrate how the pattern would fold. Inserting the dimensions of a pattern and adjusting the angles of the foldage would show if the pattern is foldable or how it would look when folded.

I utilised a free software for testing the pattern as 3D models, the Origami Simulator created by Amanda Ghassaei. It allows the importation of the patterns as svg. files, and with crease pattern marked with certain colors as mountain and valley folds, it turns the crease pattern into a mesh.

After this process it is possible to change the fold angle, to see how the pattern would fold in different fold angle percentages as shown on Image 26. It is also possible to observe the strain and the stress points of each pattern. This was very useful in the first stages of the study, because it allowed us to observe the patterns beforehand to have an idea on how they work, and it saved time from useless creasing and folding, as it was possible to check if a pattern is foldable or not. On the other hand, the file needed to be done very carefully in order to make it work in the software, and it could not process some of the patterns. (Amanda Ghassaei, Origami Simulator)

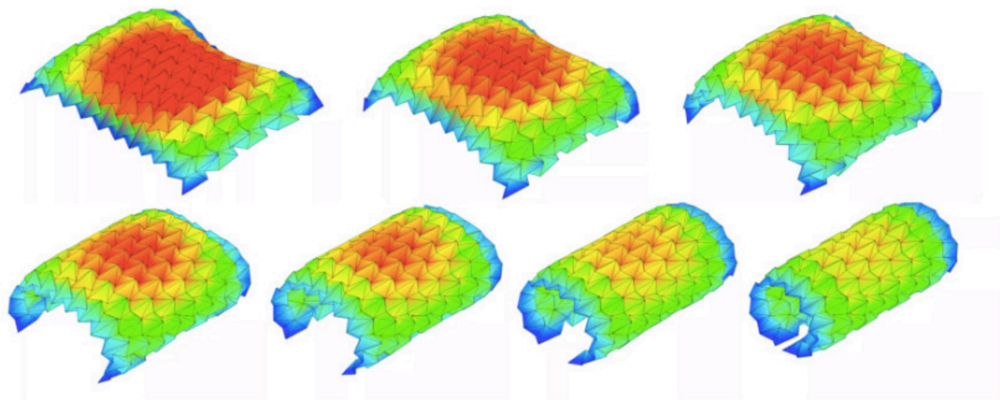


Image 26. *Waterbomb pattern shown in Origami Simulator. Red indicates the stresspoints in the folded pattern.*

Step 4: Creasing

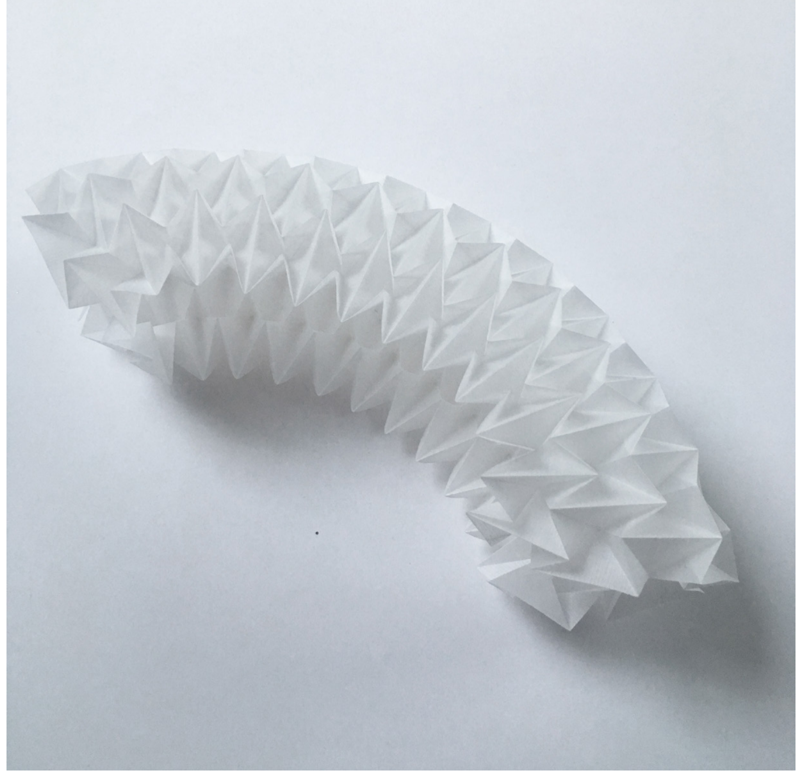
At the beginning of the project we used a laser cutter to crease the pattern on to the material, but this was not working very well for several reasons. Firstly, the laser leaves burn marks to the surface of the material, and the appearance isn't pleasing. Secondly, the laser cutter needs to be adjusted much more to make sure it doesn't cut through the material or make the cut too shallow. It also needed a lot more testing with every different material thickness and type.

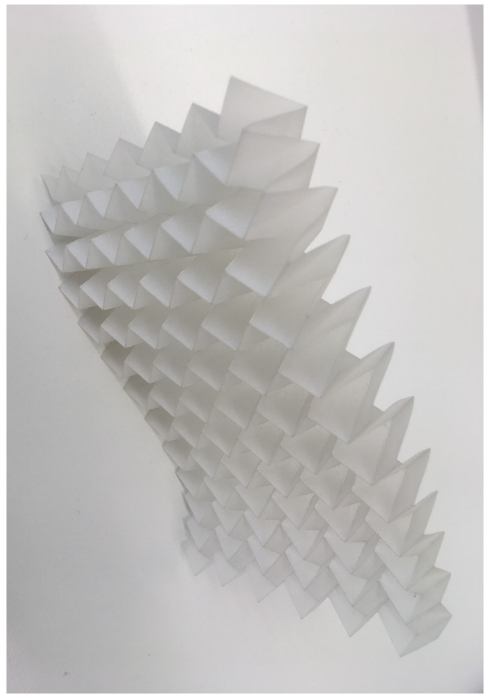
We discovered the idea to use a vinyl cutter for creasing purposes from Ekaterina Lukasheva, who presented a large amount of data on different phases of creating patterns and cutting and folding materials on her website. Based on her tutorials we decided to test a vinyl cutter for our purposes as well.

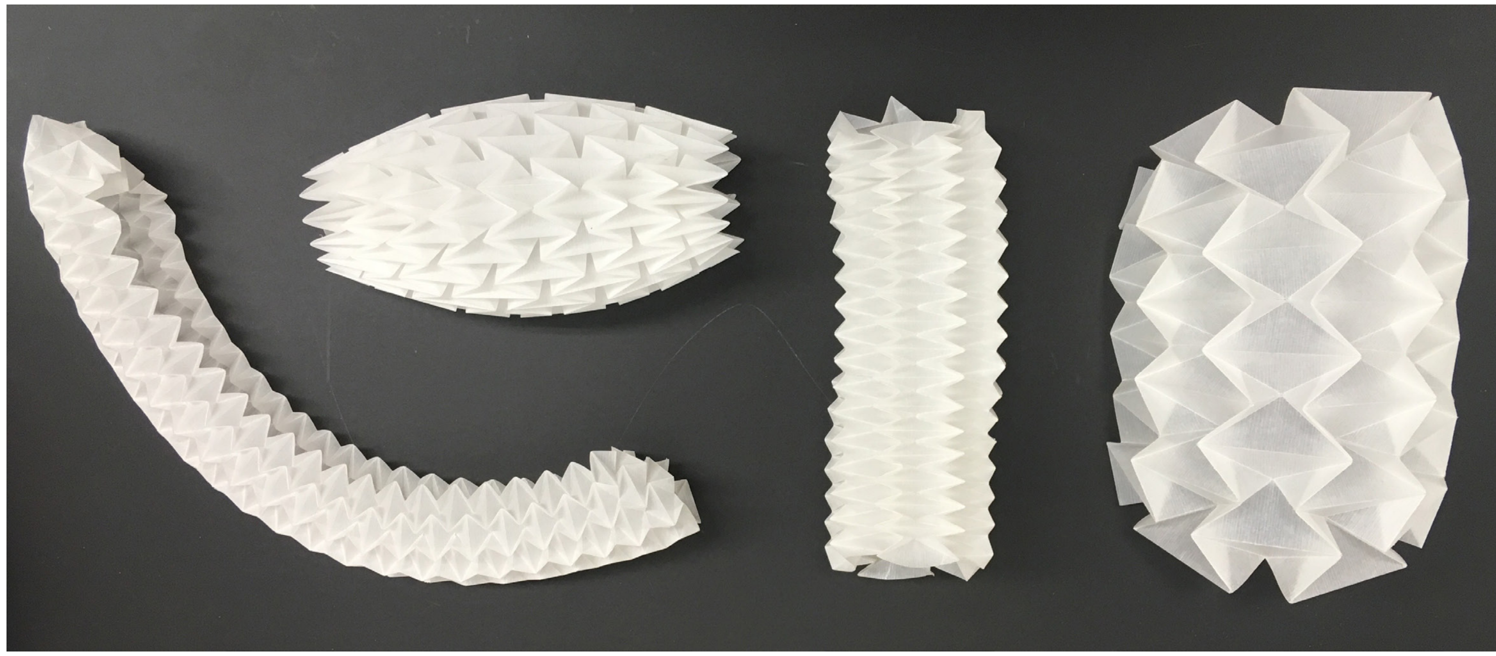
A vinyl cutter turned out to be a good way to create crease patterns, since a vinyl cutter is usually used to cut stickers, so it scratches the upper layer of vinyl but does not fully break through the material. Vector files can be directly fed to the cutter, which slightly scratches the surface of the chosen material to create folding lines, and the depth of the cut can be controlled very well.

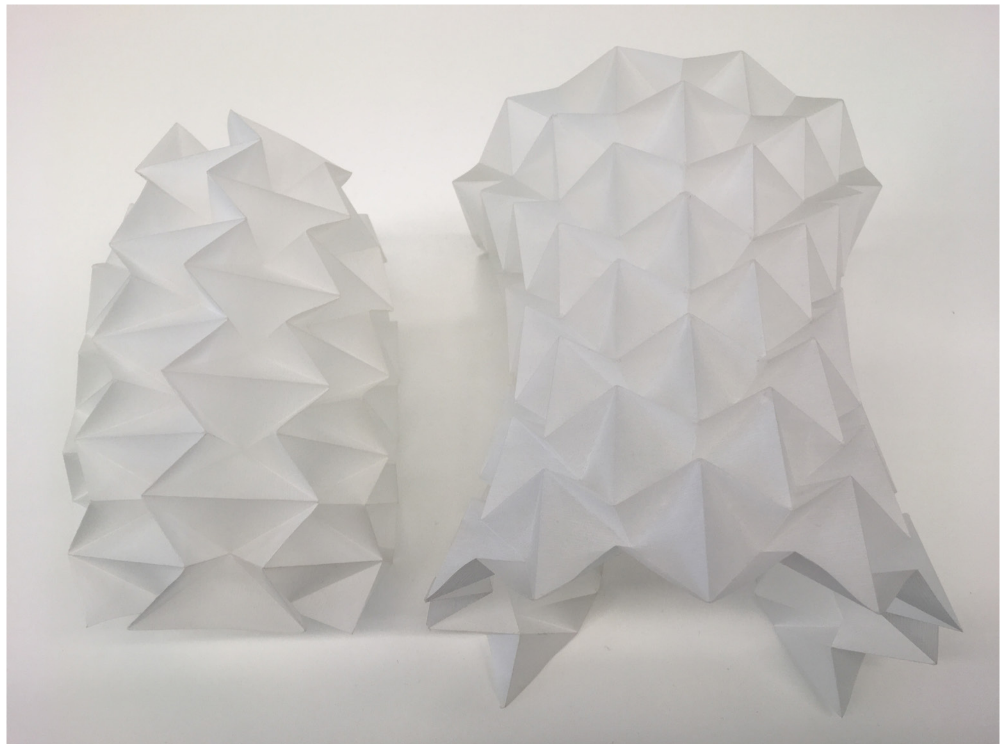
Some of the folded tests pieces done during the process to try out different patterns, shapes and structures.

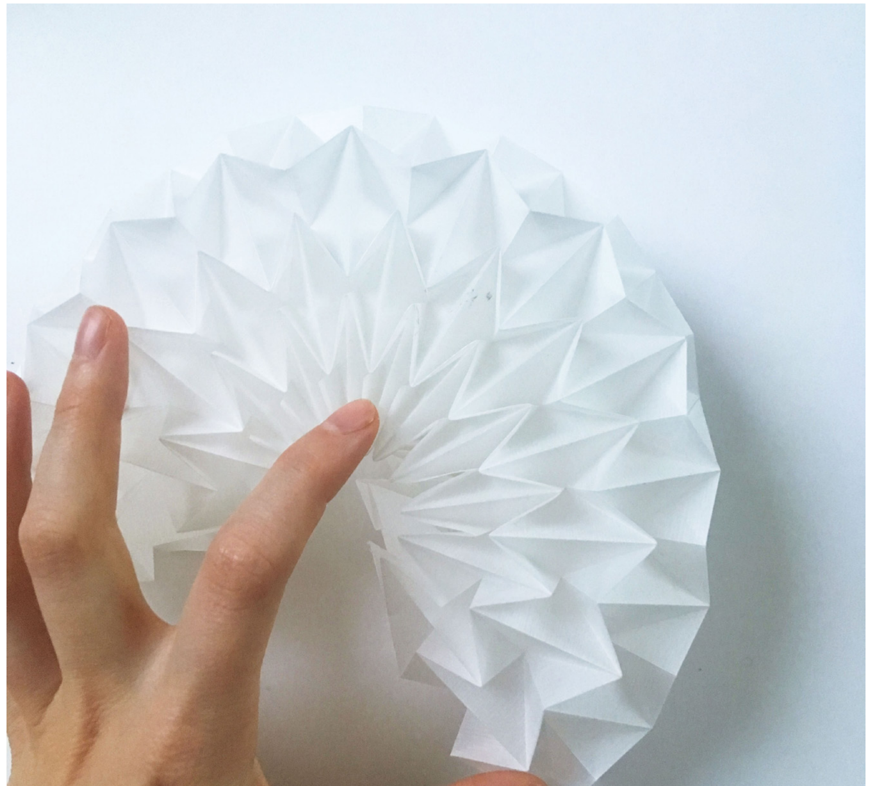
Many of the tests were done to achieve round or tubular structures.











Since the vinyl cutter is not optimised to recognize the same material, the material can not be turned to create the creases on both sides for mountain and valley folds, rather both of the lines need to be on the same side. This is not optimal in the sense of the best folding results, but for making fast prototypes to test the patterns, this was sufficient. In a longer run, the patterns should optimally be on both sides of the material, and more pressed than scratched on the surface of the board. The best solution for creating crease patterns by using machinery would be a blade cutter, where you can turn the material and create crease patterns on both sides of the material.

Step 5: Folding

After transferring the crease pattern on the surface of the chosen material, it was time to determine which of the lines were mountain folds, and which were valley folds. At the beginning it took some time to understand how the patterns needed to be folded and which point would be the best to start folding with. There are several ways to do it, but personally I found it easiest to start by folding all the longer parallel creases first.

Some patterns can be folded quite quickly, and when folded one direction, the other already starts to move into the correct formation with a slight push. Some other patterns instead will resist the fold until folded once completely flat and then the pattern will remain in a certain stage.

Folding manually is a slow process, and with the most complicated patterns it could take up to six hours to fold one piece completely. This is why looking at the manufacturing process becomes so important.

Step 6: Process conclusions

My aim was to find patterns with properties which would make them useful from a packaging point of view. I was looking for structures which would be as flexible as possible. Alternatively, I hoped to find structures which would have the ability in the pattern to pull the structure into a different shape, yet be flat foldable.

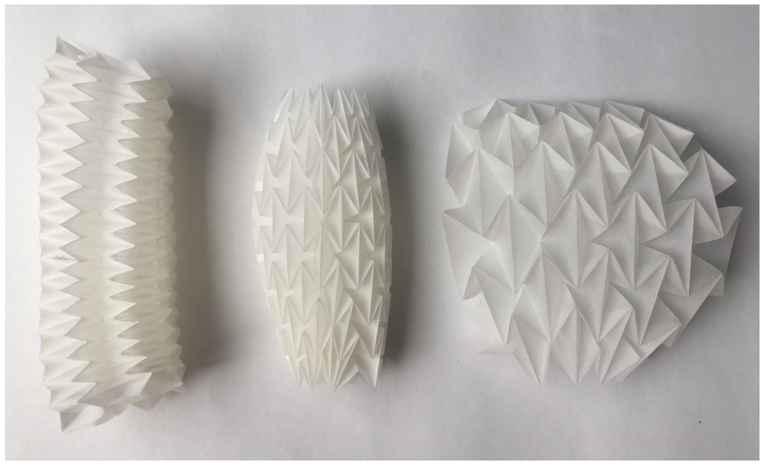
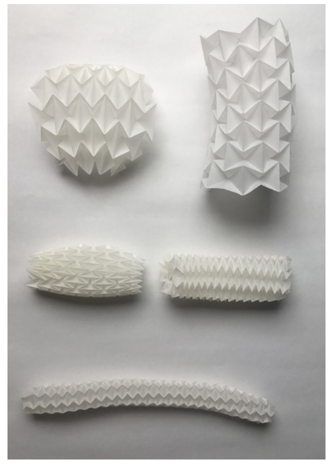
Certain patterns have immensely good features in their stiffness and capabilities to hold weight, even to the extent where they can be harnessed to replace materials such as corrugated cardboard, or even paneling in an airplane, even if the pattern material itself, non-folded, wouldn't be that strong. Creating stronger board materials would be an interesting subject worth exploring, but in my current research I was less interested in creating strong surfaces, and more interested in the variability of the shape that a pattern can turn into.

I did some experimentation with rounded and tubular structurs, and even though I found some interesting tubular shapes, the waterbomb pattern was still the most interesting to look into, because of its high flexibility and transformability. It seemed that it would be the most multifunctional pattern to use.

STUDY ON THE CHOSEN PATTERNS

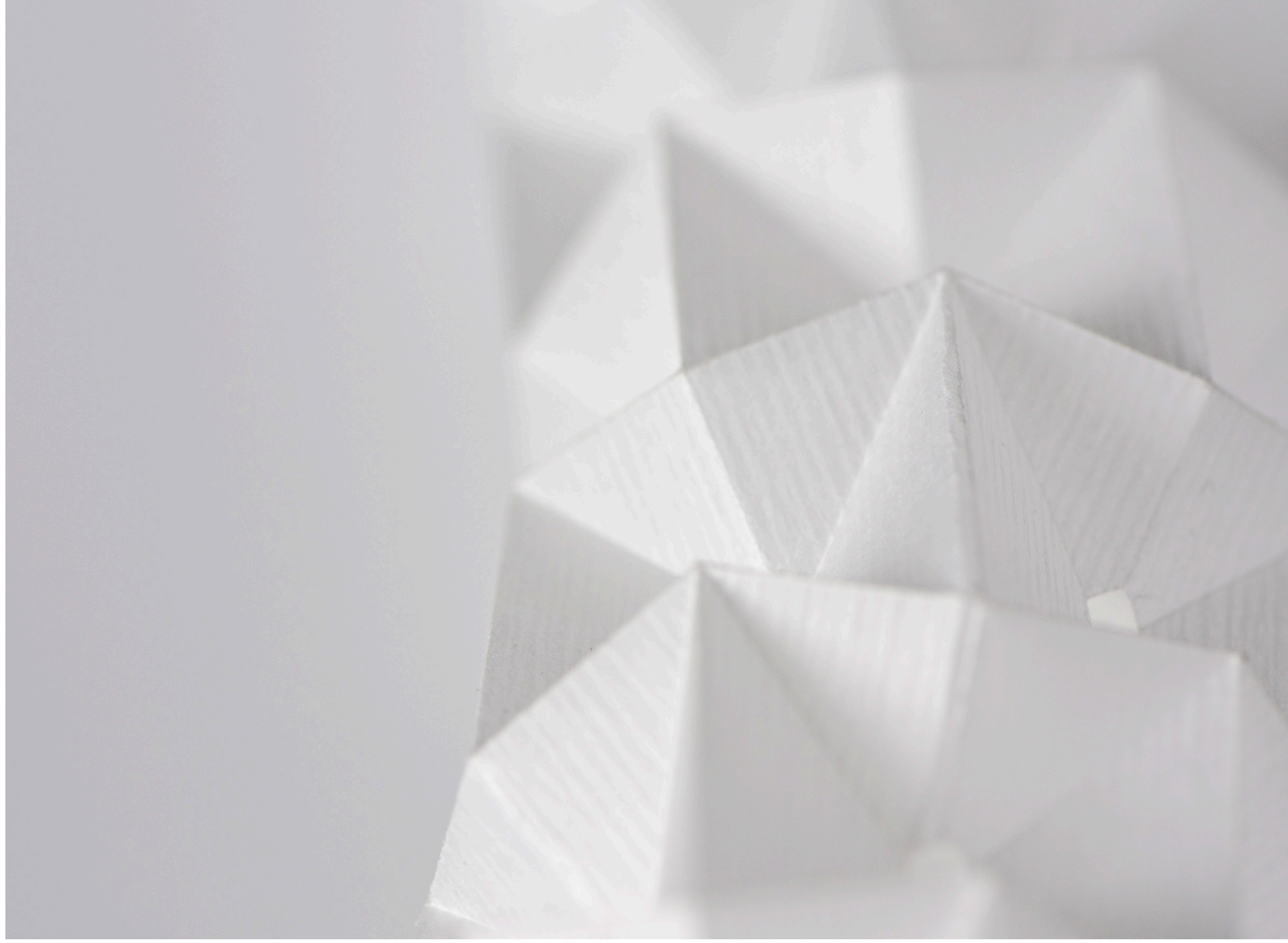
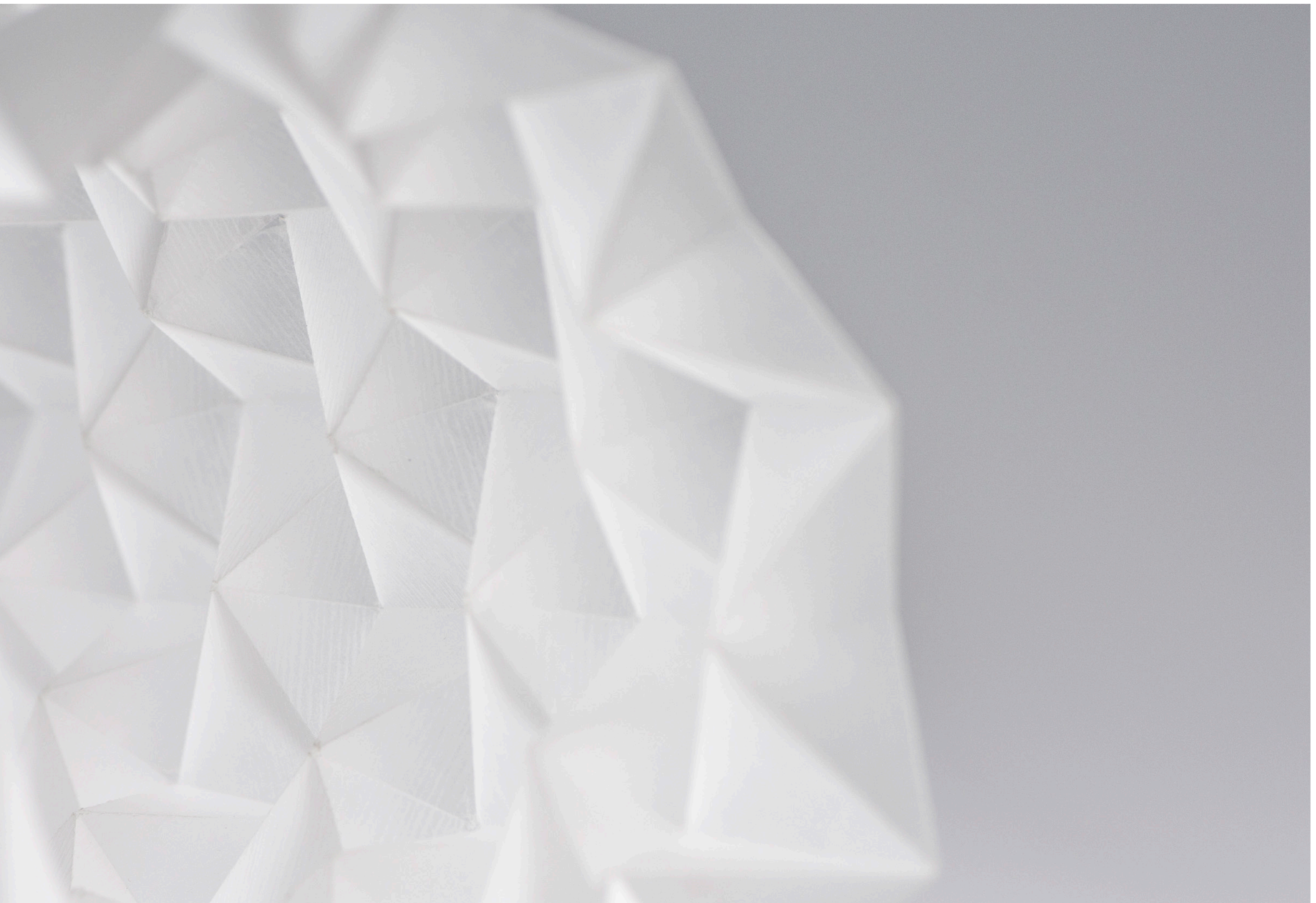
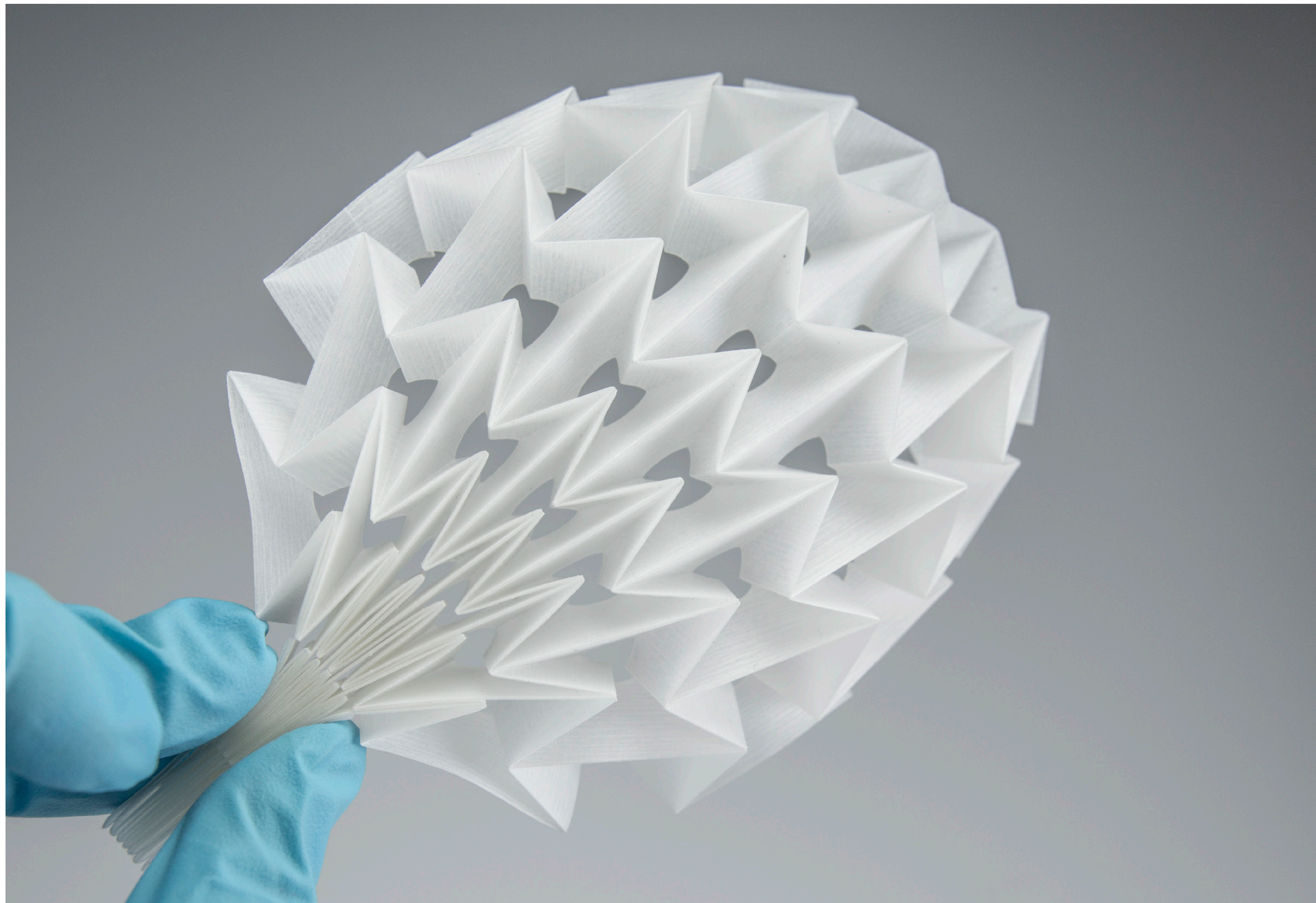
We knew quite early on that the rolling device at VTT would be based on the Miura pattern, and that had a partial effect on our decision to concentrate on Miura more than on other patterns. I was also very fascinated by the Waterbomb pattern since it was so flexible on all the directions compared to Miura, and wanted to work with that, even though it seemed like it would be extremely complicated to be manufactured.

After testing a great amount of different patterns and observing their flexibility, movabillity, strength in different directions and other qualities, I wanted to concentrate on Waterbomb pattern. This pattern has very interesting qualities, it can be turned around in many directions which changes its shape but it still keeps its flexibility and stays in a form. I started to test what happens when changing its parameters, scaling the pattern longer on one direction and then doing the same with the other way around. This led to very different kind of structures from an extremely rigid tube structure to the opposite, a very loose structure that didn't bend almost at all to any directions.

Images 27 & 28. *Experimentations with different dimensions of the Waterbomb pattern.*

Next page:
Images 29.-32. *Pattern test results, Photos by Valeria Azovskaya.*

I came to the conclusion that the original Waterbomb pattern has the best structural abilities: an even square base on the pattern made the material the most flexible compared to the variations I tested. With 2mm times 3 mm holes pierced to the “middle” corners of the pattern it was less complicated to fold and less stiff.

In addition to tests made with the Waterbomb pattern, I made variations using the principles of Miura-ori pattern, placed on a long strip of paper board, to achieve cup-like shapes with it and to make it possible to wrap it around an object, in this case bowls and plates. Using this pattern, the same structure didn’t work on different sized and shaped objects as in Waterbomb based patterns, which flexed on the directions it needed to.

I made a system on how long each singular segment of a pattern needed to be, and then adding or removing these segments made the pattern the right size to each object to be packed. With this pattern, I started with a long accordion-like folds, then folded a pattern of Miura on the middle and adjusted the top and bottom layers of fold so that the angle of the finished folds turned on an optimal degree to fold under and on top of the tableware.

MATERIAL TESTING

Testing the paper and board materials was an essential part of this study. Different materials act in different ways when folded or bent, and it was clear from the beginning that the properties of the paperboard have a large impact on foldability. One of the goals of the project was to use bio-based sheet materials, to find solutions to replace plastic packaging, but there wasn’t any specific choice of material set by the research project.

Paper board is not a homogenous material, which means that its properties need to be looked at when folded and a certain direction must be chosen for the best end result. The direction of the fibres in the paper board have a large effect on the folding process. The optimal grammage for folding is also important to study. An even strain is needed for the material not to break, as most of the energy in the folding process is centered to the corners and edges.

In the first part of prototyping, we used Icepaper, which had perfect qualities for folding, but was not the most ecological choice, because it had an underlayer of plastic film. This made the foldability of the material excellent, since it was at the same time stiff and still had a lot of strain. It led us to look for materials that were cellulose-based papers and paperboards, but had similar qualities. We aimed to find material properties that made the folding better and would have enough of strain and still be strong, so that the material wouldn’t rip or start to crack easily, and would enable the material to hold its structure after folding.

KOTKAMILLS SAMPLES

KotkaMills provided us some board materials to use. The sampled boards were Absorbex eco, Isla cup base, and Aegle pro, all in several different grammages. This gave us a good view of the material properties that the paper board needs to have for optimal folding capabilities. I used Miura pattern for the test samples because it was easy to fold and I got fast results, but it also has sharp enough angles, which made it easy to compare material properties. Aegle pro was thicker than the other sample materials and had a stiff surface layer which created some breakage of the material when folded. Absorbex eco worked well for folding and had enough stretch to prevent it from breaking, but being hand folded, it seemed too soft to fold precisely and it absorbed moisture from fingertips leaving the results less sharp and exact. Isla cup base worked perfectly on all its thicknesses. It is the same material as used in paper cups, and the strain of the material was optimal for folding it without breaking the material.

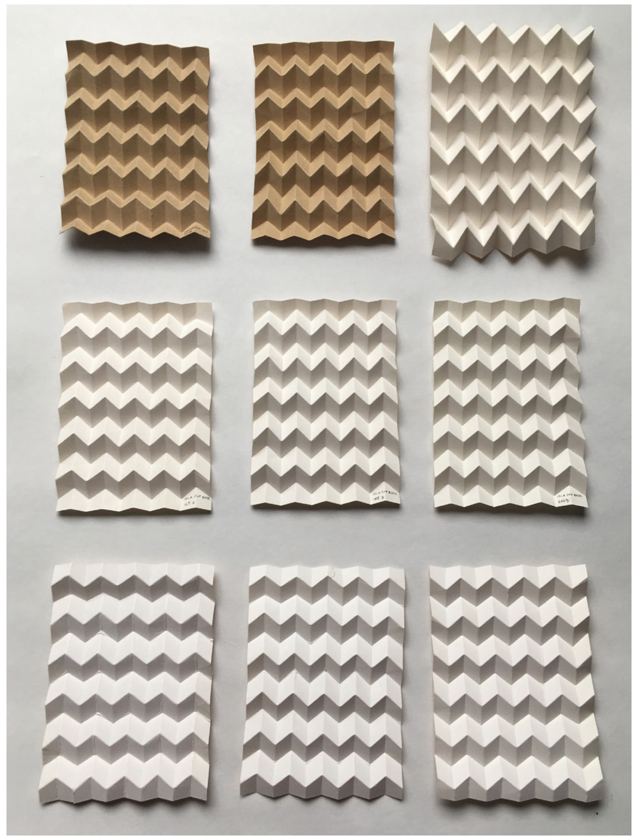


Image 33. *Kotkamills material samples.*

Image 34. *Breakage in the Aegle Pro sample*

Depending on the use, all the tested Isla samples were working well, but to achieve a shape which was stiff enough to stay on a chosen position and not to wobble around, the 165gsm was excellent, yet still easy enough to fold. The material I used for my final samples was Isla cup base 165gsm from Kotkamills. I was very happy with the solutions from all Isla cup base grammages that I tested, since the strain in this material was optimal for folding.

TESTING MANUFACTURING POSSIBILITIES

For testing the manufacturability of the folded material structures, a rolling nip device was developed by VTT as part of the research. It was used for testing the industrial folding capability of the Miura pattern. The rolls press the pattern to board materials fed between the rolling nips, but the angle of the folds would need to be deeper to achieve a better folding solution. As with manual folding, pre creasing the material would have improved the end result. To create a better solution the folding should happen slowly, phase by phase, with several rollers that have deepening angles and that would first fold the creases that are in the same line with the direction of the rolling.

The nip device brings forth several limitations. The width of the folded material on the other direction is limited. The pattern also needs to have a clear direction so that the pattern can be clearly folded from one edge to another: instead of being able to start from the middle or the corners, the pattern needs to have parallel lines that fold. The angle of the pattern on nips needs to be sharp enough to actually fold the material, but if it is too sharp, the material won't take the pressure and it will start breaking. The only way to do this would be by using several rolling nips that slowly bend the paper board phase by phase.

To test the foldability of the Waterbomb pattern, a 3D printed test segment was ordered by VTT and manufactured by Aava tech for molding a pattern. The two mirrored pieces of the 3D printed test segments are pressed against each other to see how it affects the paper board. This gave a lot of information: It became clear that the pattern needs to be pressed slowly from the one side to the other, to prevent the material to start breaking from the middle. (Not pressing them directly against each other). Also, creating holes to all the sharp corners of the crease pattern made the pattern much easier to fold with this method, and prevented the material from ripping from the corners.

This showed quite clearly that either the material should have very high strain (as plastics usually have) or the pattern would need to be pressed to its shape in a slower, more gentle method. It would also be preferable if there were similar molds on different levels of the foldage, starting from just slight angles turning all the creases to right directions and then proceeding with sharper angles for the folds.

CONCLUSIONS

During the research I developed a more intuitive understanding of how different type of materials react when folded, yet it is difficult to know if a material works well for folding purposes without testing it. The first thing to try would be to bend a piece of the material. If the material starts cracking easily, it will most likely crack when folded too. However, most materials can be folded despite of that, as long as they are treated the right way.

Most importantly, in many cases, making the crease patterns is more important than what the material itself is. If the material is very thick or has a heavy coating, it is more likely to start breaking from the creases, and if the material is too thin, it will be very difficult to fold as it is most likely won't be stiff enough to hold its shape.

I noticed that the ideal material for folding would be close to plastic as its properties, stiff but high strain. Homogenous and even, and transformable to any shape. This material might not exist yet, but it could be possible to be made from cellulose, since it has been processed into plastic-like materials already.

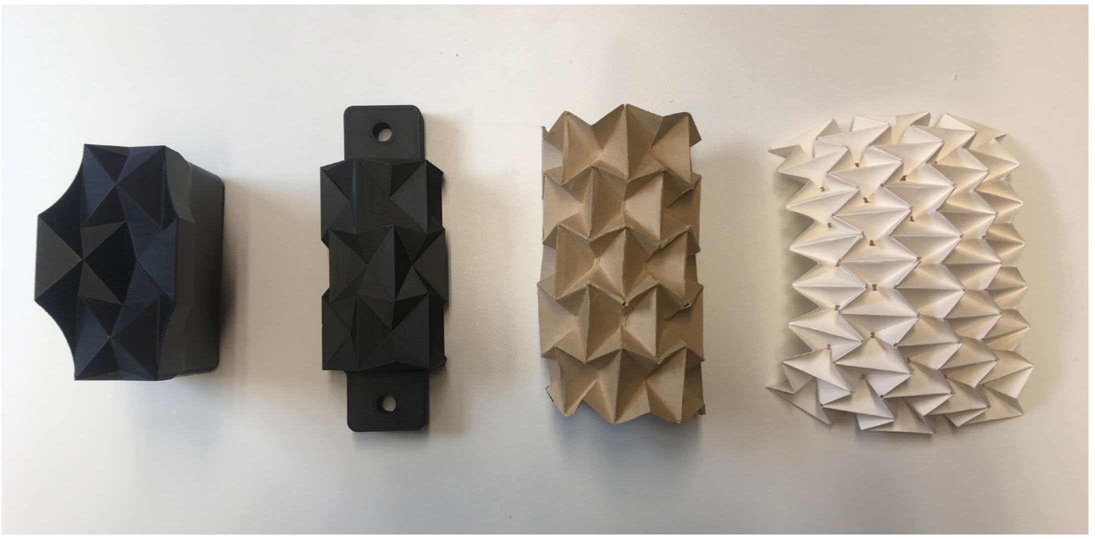


Image 35.
A 3D printed test segment with the waterbomb pattern, and two material test pieces molded with it.

APPLICATIONS

As I got interested in looking for a specific function for the folded structures and the protective capabilities of these structures can have, I started to think of solutions that could work well for example packaging glass or other fragile materials. Concentrating on the shape of the object that is being packaged, and the possibility to make a structure that would wrap well around an object and hold it in place inside the package was something that I wanted to focus on.

PACK-AGE TEAM FISKARS

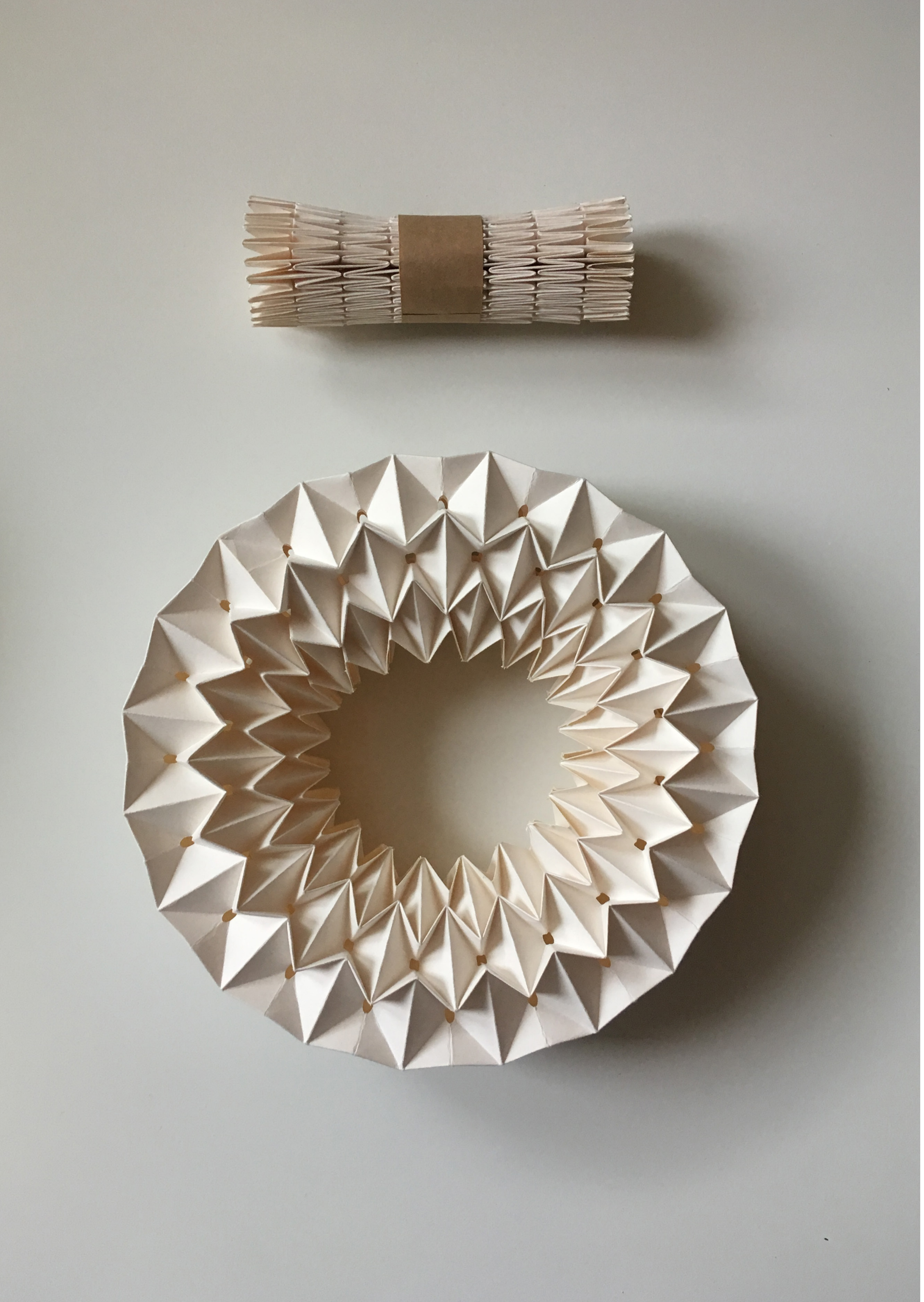
In a very early phase of the study, I was asked to fold some prototypes for a possible packaging solution that was designed for Pack-Age packaging course, by a team that was making their coursework for Fiskars e-commerce packaging. They already had a packaging for the task but they wanted to add a foldable solution, so I created a few options for their use. These were also shown to a target group as a part of a survey, and the folded pieces got good feedback for their appearance and sustainability.

The task was to design and fold samples that could protect Iittala tableware inside an e-commerce packaging. The samples needed to work inside the package regardless of the size and quantity of the objects sent in the package. The samples also needed to replace extra wrapping paper or plastic wrappings which the boxes are usually filled with to protect the products.

The pieces I made for this project were based on the Waterbomb pattern and an adjustment of the Miura pattern. Using these patterns for the Fiskars packaging project made me realize how well the Waterbomb pattern sets around different shapes and sizes because of its flexibility towards several directions at once. Since the shape of tableware is mostly a solid of revolution, I concentrated on designing patterns that would work around rounded objects. This also applied with Miura based solutions that I made.

The pieces I made for this Pack-Age project led me to experiment these two types of patterns in more detail, and also reinforced the idea of working with packaging material prototypes that would protect tableware.

Image 36. and 37. *Pieces made for Team Fiskars, Iittala e-commerce packaging.*



THE FINAL SAMPLES

Based on this project, I continued developing the two types of patterns I had used, Miura and Waterbomb, to refine the shapes and make more variations of the patterns. At this point, it seemed that the Waterbomb pattern would be extremely difficult to achieve in industrial manufacturing because of how it curves up when it's folded, and because of the certain edges that "hit" each other when folded. This led to some tests to remove the parts that were causing trouble, making holes to the material. This affected the foldability quite a bit and the material was much easier to fold, yet the good abilities of the pattern remained the same. Pierced holes on all the pattern edges made the folded pattern less tight, and softer to handle.

Since I discovered that the Waterbomb pattern tends to shape into a tube-like structure when folded, I created donut-shaped pieces that fit around plates and bowls. I found out that the same pattern and even the same size can easily adjust around different shaped tableware, as long as the objects were spherical.

The pieces I created work as cushioning inside a regular package, and protect the object from breaking. In addition to the Waterbomb based pieces, I also designed cushioning materials using the Miura pattern. These pieces didn't work in the same way as the pieces with Waterbomb pattern. When applying the Miura-based pattern, the folded pattern needs to be measured in height to fit the objects, and the height defined how many layers of the pattern was set between the top and bottom folds. On these pieces, another outer packaging wouldn't necessarily be needed, but instead, a ring of board going around the shape, that could also have branding content on it.

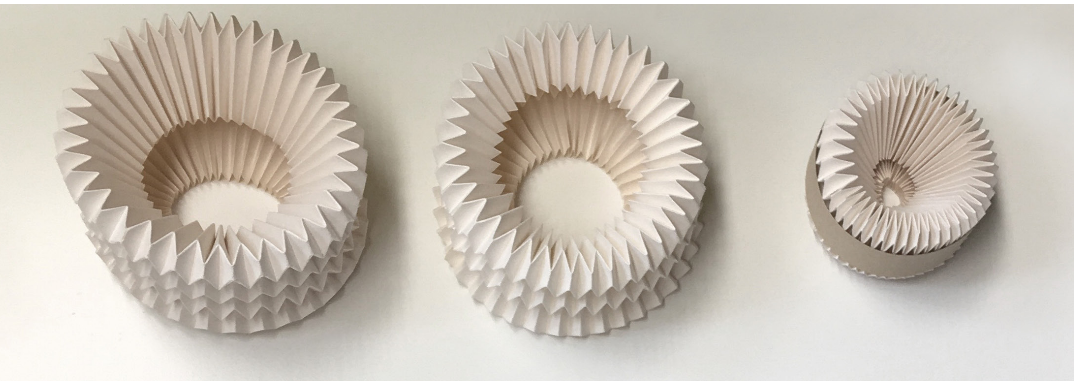
Some of these pieces were exhibited during the Aalto Graduation Party exhibition and Helsinki Design Week exhibition 2019, and they received very good feedback. The structural design of the patterns raised a lot of interest because they weren't something people had seen that much before. The movability and flexibility of the structures was considered fascinating, and people who saw the packages wanted to touch them and see how they worked.

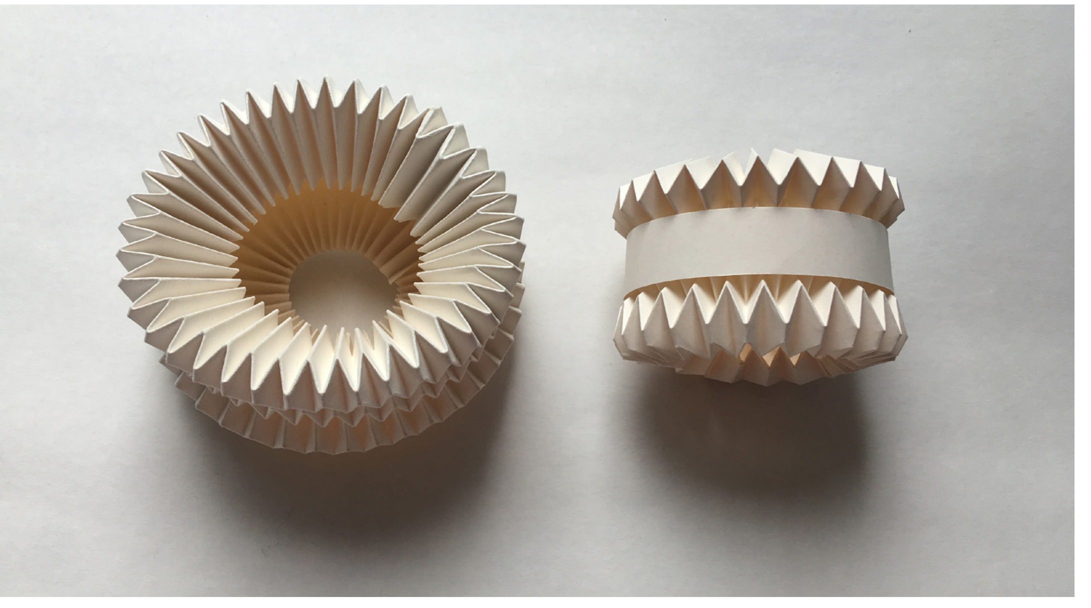
APPEARANCE AND USER EXPERIENCE

The most common current solution for protecting fragile materials inside a packaging is bubble wrap or other similar material. If the product is precious, such as fine and expensive tableware, finding a lump of bubble wrap inside, taped over the product, can feel very disappointing. The wrapping does not correspond to the brand promise if the outer package looks very refined, nor does it prepare the user to enjoy the fine tableware inside. Moreover, after unwrapping the objects, the customer is left with a piece of plastic they have no use for, which will immediately end up in the trash.

Instead of trash, there could be a nice surprise inside the package: an interesting, sustainable option wrapped tightly around the objects, and even if the customer would not want to save the material, it would be easily collapsible into a small roll and then recycled with boards. It could also be used as a container for storing the tableware for rarer use, or the packages could be stored and utilized during transportation, such as moving from one house to another or taking the tableware to an event location. The packages could also be used when a customer buys the tableware from the store, so that it could be easily carried home or cushioned as it is given as a gift.

Besides offering a more economical solution with a tessellation pattern made into paper materials, this product also contributes to an improved visual experience in terms of opening packages and finding the products inside. The material of the cushioning materials I created has a beautiful cream color. In addition to this, the holes pierced to the pieces with Waterbomb pattern reveal the color and some details of the product inside the structure in a very intriguing way. I felt I was able to produce delicate and interesting samples which add value to the packaging by improving user experience. While they look precious and are very lightweight, they still hold strong to any compression around the objects they protect. The material is strong, light and beautiful, which makes them visually compatible with beautiful and precious objects.





CONCLUSIONS

Some essential properties of packaging are to preserve and protect products inside the packaging while being appealing from the customer point of view and maintaining a positive user experience as opened and closed. The goals of this research project were to find suitable origami tessellation patterns for the use of packaging design and industry. The properties of folded origami tessellations can offer a lot of solutions for different structural challenges faced in packaging. The aim was to search for patterns that would have similar benefits that plastic materials have, such as high flexibility, transformability and being lightweight, while making a more sustainable solution to plastic materials. One of the main goals was also to find patterns that could be industrially manufactured from renewable cellulose based materials to be able to replace some of the plastic materials in packaging.

While paper board is already used as a packaging material, it has its limitations when it comes to different shapes in the packaging structure. Since paper board is a sheet material, it is mostly used for box-shaped packages, and compared to plastic, the shapes that can be created with it are very limited, since plastics can be formed into any kind of shape. When using paper board as packaging material the biggest limitation is the shape. In addition to this, if the product inside the packaging needs protection during transportation, sheet materials are usually not enough, and the package will need some cushioning material as well. This cushioning material is usually plastic, styrofoam or bubble wrap. Compared to these materials, paper and paper boards are reusable and renewable, so the lifecycle of the material is longer and won't strain the environment as much.

Kraft paper is also used as cushioning material, with long pieces that are wrinkled around the object that needs to be protected. Kraft paper is not a visually pleasing option, a lot of material is needed to fill the packaging, and it will go directly to waste, so this is not a good option either from customer experience perspective or from an environmental point of view. One option is also to make a structure following the original shape of the object inside the outer package. This solution can usually be found in cosmetic packaging. However, when this method is used, each structure must be made individually for each product, which is time-consuming and complex.

The Waterbomb pattern could be applied to any sheet material, but for the purpose of creating a protective structure, a paper board works best, since it's a soft material that won't harm the object inside the packaging. These kind of paper structures could also be covering the inside surfaces of a regular board box, and used in this way, they would allow more protection for the object which has been packaged. The Waterbomb structure, made out of any sheet material, is very strong against compression.

In terms of folding, the most important property in a paper board is strain, and the material needs to have enough strain not to break. The paper board cannot be too thick either, and if it breaks while bent, folding it will be very difficult. The direction of the fibers on the board also have a large effect on the success of the folding process.

In terms of academic properties of the research, the outcome of this research was a more profound understanding of the patterns and of the functionalities of different tessellation patterns which created ideas on how to use them for different purposes in design. The practical outcome of this project was a series of folded structures that function as cushioning materials for packaging tableware. The patterns are adjustable for different sizes and shapes, and theoretically could be manufactured with a rolling nip device after some further development.

LIMITATIONS AND FURTHER RESEARCH

One could argue that creating such complicated structures as origami tessellations, would not be as good a solution as continuing to use simple cardboard boxes. However, I would argue that the functionalities of this new structural material are much more varietal than those of cardboard boxes, since it has the abilities to stretch and fold flat and it is highly transformable and flexible. A tessellated structure makes the package stronger and more suitable for fragile objects, for example tableware or glass bottles.

The downside of this kind of folded structural materials lie in the manufacturing process which has its challenges, and would be needed to be resolved in the future. If compared to regular card packages, the material consumption of these folded structures is obviously higher, but compared to plastics it is yet again a more environmental solution.

The manufacturing question was still left open to the extent of this study. The manufacturability of the Waterbomb pattern is quite certain, and it has been done elsewhere, but finding or creating the machinery is not that simple, and would need to be studied further. Waterbomb pattern has a lot of challenges, but based on the tests that were made during this research, manufacturing of it should be possible.

Testing the patterns in real life with real machines is still different from the techniques used during this process so it can not be said with a 100 percent confidence that the patterns would work in industrial manufacturing. The manufacturing possibilities of the patterns were investigated with the help of VTT and tested with a prototype of a rolling nip machine, but this part of the research would need a longer period of time to be studied. There is a huge variety of different patterns that could work for many types of packaging needs and it would be interesting to continue to study and develop these ideas further in the future.

I present that these patterns could be an excellent solution to replace some plastics such as bubble wrap and styrofoam from for example e-commerce packaging and other packages that need to have cushioning for the products to protect them.

As the folding device is developed further, it will offer more interesting points of research. The folding device could be used for other types of packaging designs as well. Deployable structures would be an extremely interesting subject to look further into, since there are so many different opportunities in this field. In the future, it would also be interesting to study how curved folds could be implemented to packaging, and weather similar manufacturing methods could work for curved structures as well.

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REFERENCES

Alsina, Claudi & Nelsen, Roger. (2010), Charming Proofs: A Journey Into Elegant Mathematics, Dolciani Mathematical Expositions, 42, Mathematical Association of America, p. 57, ISBN 978-0-88385-348-1.

Basily, B. B. & Elsayed, E. A. (2004). A Continuous Folding Process for Sheet Materials. Department of Industrial and Systems Engineering Rutgers University. (Retrieved: https://pdfs.semanticscholar.org/9c27/cf9f0a8bf6a4b7c0e2e3f428d3668d190a2f.pdf?_ga=2.107082242.1699264742.1565871168-418231016.1565871168 15.8.2019)

Candy, Linda. (2006). Practice Based Research: A Guide. Creativity & Cognition Studios, University of Technology, Sydney, CCS Report: 2006-V1.0 November (Retrieved: https://www.researchgate.net/publication/257944497_Practice_Based_Research_A_Guide 14.8.2019)

DiLeonardo-Parker, Benjamin. (2016). Six Simple Twists: The Pleat Pattern Approach to Origami Tessellation Design. USA: CRC Press, Taylor & Francis Group.

DuPuis, Steven & Silva, John. (2008). Package design workbook: The art and science of successful packaging. USA: Rockport Publishers, Quarto Publishing Group.

Ellicott Candace & Roncarelli Sarah. (2010). Packaging Essentials : 100 Design Principles for Creating Packages. USA: Quarto Publishing Group.

Fei, L.J. & Debnath, Sujan. (2013). Origami Theory and its Applications: A Literature Review. International Journal of Social, Business, Psychological, Human Science and Engineering. 7 (1): pp. 113-117.
(Retrieved: https://espace.curtin.edu.au/handle/20.500.11937/2911 25.8.2019)

Garcia, Xochitl. (2017). Science Friday, Tessellations and Miura folds. (Retrieved: https://www.sciencefriday.com/educational-resources/tessellation-and-miura-folds/, 5.8.2019)

Gjerde, Eric. (2009). Origami Tessellations - Awe-Inspiring Geometric Designs. USA: CRC Press, Taylor & Francis Group.

Greicius, Tony, (2014). Solar Power, Origami-Style. NASA. (Retrtieved: https://www.nasa.gov/jpl/news/origami-style-solar-power-20140814, 5.8.2019)

Jackson, Paul. (2011). Folding techniques for designers - From sheet to form. UK: Laurence King Publishing Ltd.

Järvi-Kääriäinen, Terhen & Leppänen-Turkula, Annukka. (2002). Pakkaaminen - perustiedot pakkauksista ja pakkaamisesta. Suomi: Hakapaino Oy.

Koskenlaakso, Leena. (2017). Uudenlaista liiketoimintaa selluloosasta. (Retrieved: https://www.vtt.fi/Impulssi/Pages/Uudenlaista-liiketoimintaa-selluloosasta.aspx 25.4.2019)

Lang, Robert. (2003). Origami Design Secrets: Mathematical Methods for an Ancient Art. USA: CRC Press.

Lang, Robert. (2018). Twists, Tilings and Tessellations - Mathematical Methods for Geometric Origami. USA: CRC Press.

Miller, Laurel & Aldridge, Stephen. (2012). Why shrink-wrap a cucumber - The Complete Guide to Environmental Packaging. UK: Laurence King Publishing Ltd.

Neufeld, Len & Stassen, Fabienne & Sheppard, Ruth & Gilman, Terry (edit.). (2016). World Economic Forum. The New Plastics Economy - Rethinking the future of plastics. (Retrieved: http://www3.weforum.org/docs/WEF_The_New_Plastics_Economy.pdf, 1.8.2019)

Plastic in the ocean: the facts, effects and new EU rules. (2018). News, European Parliament. (Retrieved:http://www.europarl.europa.eu/news/en/headlines/society/20181005STO15110/plastic-in-the-ocean-the-facts-effects-and-new-eu-rules, 1.8.2019)

Shijian, Lin; Yuquig, Tang & Wentao, Lin. (2017). Flexible Packaging. HK: SendPoints Publishing Co., Ltd.

Smith, Hazel & T- Dean, Roger. (2009). Practice-led Research, Research-led Practice in the Creative Arts. Edinburgh University Press.

Sternberg, Saadya. (2010). Symmetry issues in collapsible origami. Published in Symmetry: Culture and Science, vol. 21, number 4, pp. 345-364. (Retrieved: https://www.researchgate.net/publication/268995619_Symmetry_issues_in_collapsible_origami, 22.08.2019)

Trebbi, Jean Charles. (2012). The Art of Folding - Creative Forms in Design and Architecture. Spain: Promopress.

Vaughan, Laurene. (2017). Practice-based Design Research. Bloomsbury Academic.

Wang, H. & Zhao, D. & Wang, M. & You, Z. (2018). Fabrication of Polymeric Origami Tube. In: Origami 7: The Proceedings from the Seventh Meeting of Origami, Science, Mathematics and Education. Edit.: Lang, Robert & Bolitho, Mark & You, Zhong. UK: Tarquin Publications. Pages: 827-833. ISBN (Vol 3): 978-1-911093-91-6

Wang-Iverson, Patsy & Lang, Robert J. & Yim Mark. (2016). Origami 5: Fifth International Meeting of Origami Science, Mathematics, and Education. USA: CRC Press.

OTHER WEB RESOURCES

About Robert J. Lang, Bibliography. Retrieved: https://langorigami.com/about-robert-j-lang/ 15.8.2019

Amanda Ghassaei. Origami Simulator. Retrieved: http://apps.amandaghassaei.com/OrigamiSimulator/ 5.8.2019

FinnCERES Research. Retrieved https://finnceres.fi/research/ 1.8.2019

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Images 24. & 25. Aube Bag-in-a-Box Wine.
https://www.packagingoftheworld.com/2014/11/packplay.html

Image 26. Waterbomb patttern shown in Origami Simulator. http://apps.amandaghassaei.com/OrigamiSimulator/

Image 29.-32.. Pattern tests. Photos by Valeria Azovskaya.

Image 36. and 37. Pack-Age Team Fiskars. Photos by Elina Rantanilkku.